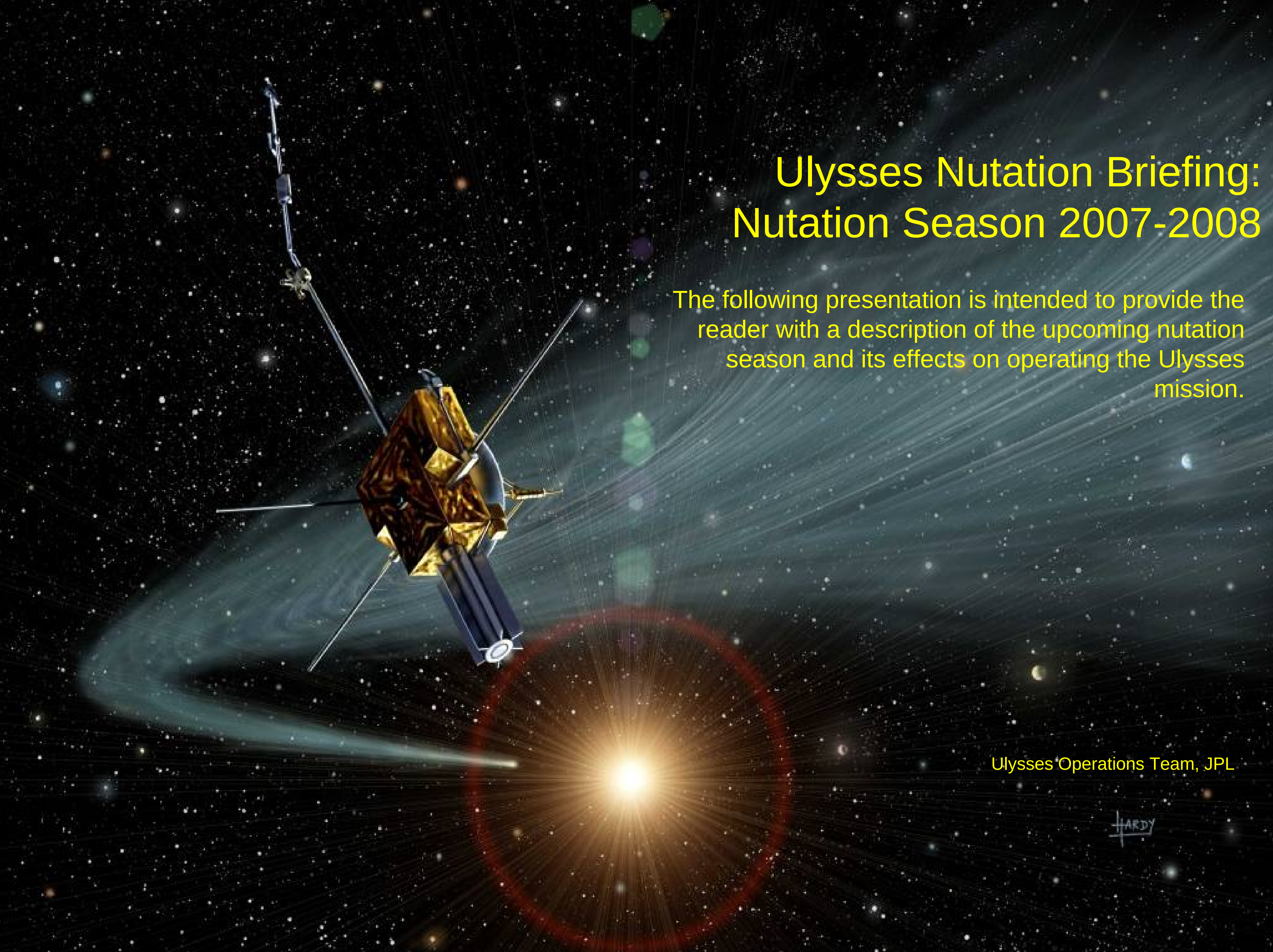
Ulysses Nutation Briefing: Nutation Season 2007-2008

The following presentation is intended to provide the reader with a description of the upcoming nutation season and its effects on operating the Ulysses mission.

Ulysses Operations Team, JPL



Ulysses Nutation Briefing:
Nutation Season 2007-2008

What follows is a brief overview of the Ulysses mission, for more in depth material go to

http://ulysses-ops.jpl.esa.int/

Or contact the Flight Control Team at

ulssci@jpl.nasa.gov

The Ulysses mission is a joint undertaking between the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). Its goal is the exploration of the Sun's environment far out of the ecliptic plane. Ulysses is the only spacecraft to have visited this unique region above and below the poles of the Sun.

Ulysses Nutation Briefing: Nutation Season 2007-2008

The purpose of this presentation is to discuss the Ulysses nutation anomaly, both its nature, and in terms of its effect on mission operations. While also discussing past nutation seasons specific attention will be paid to the forthcoming nutation season in 2007-2008, discussing planned operations and ground station coverage issues.

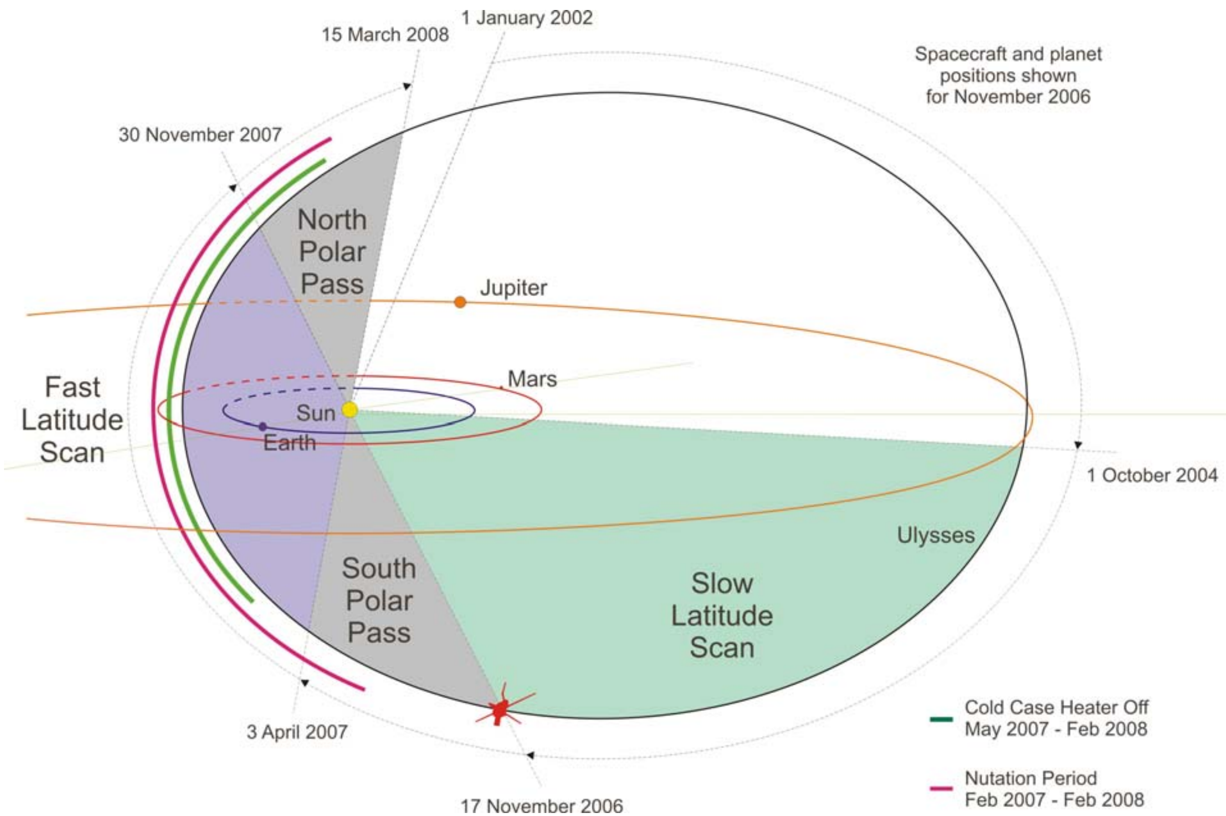
The presentation will cover the following topics:

- Mission Overview
- Spacecraft Overview
- Nutation Anomaly
- Outcome Of Uncontrolled nutation
- Nutation Control Tools
- Ground Coverage
- Operations Strategy For Upcoming Season

Mission Overview

For a more detailed Mission Overview presentation, click here

Ulysses' orbit is unique. It is inclined approximately 80° to the ecliptic plane, allowing it to survey the Sun at solar latitudes. Ulysses' heliocentric range varies from approximately the heliocentric range of Mars to that of Jupiter. The one way light time (OWLT) varies from less than 5 minutes, up to 53 minutes at maximum Earth range.

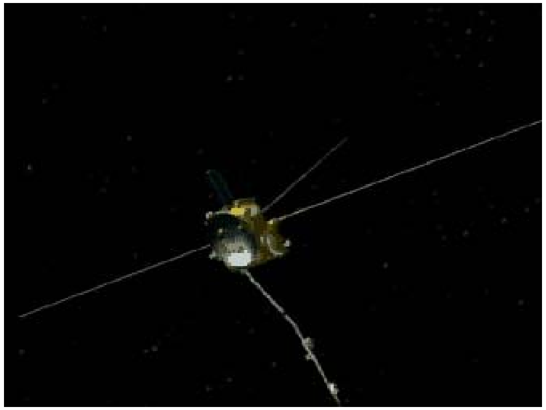


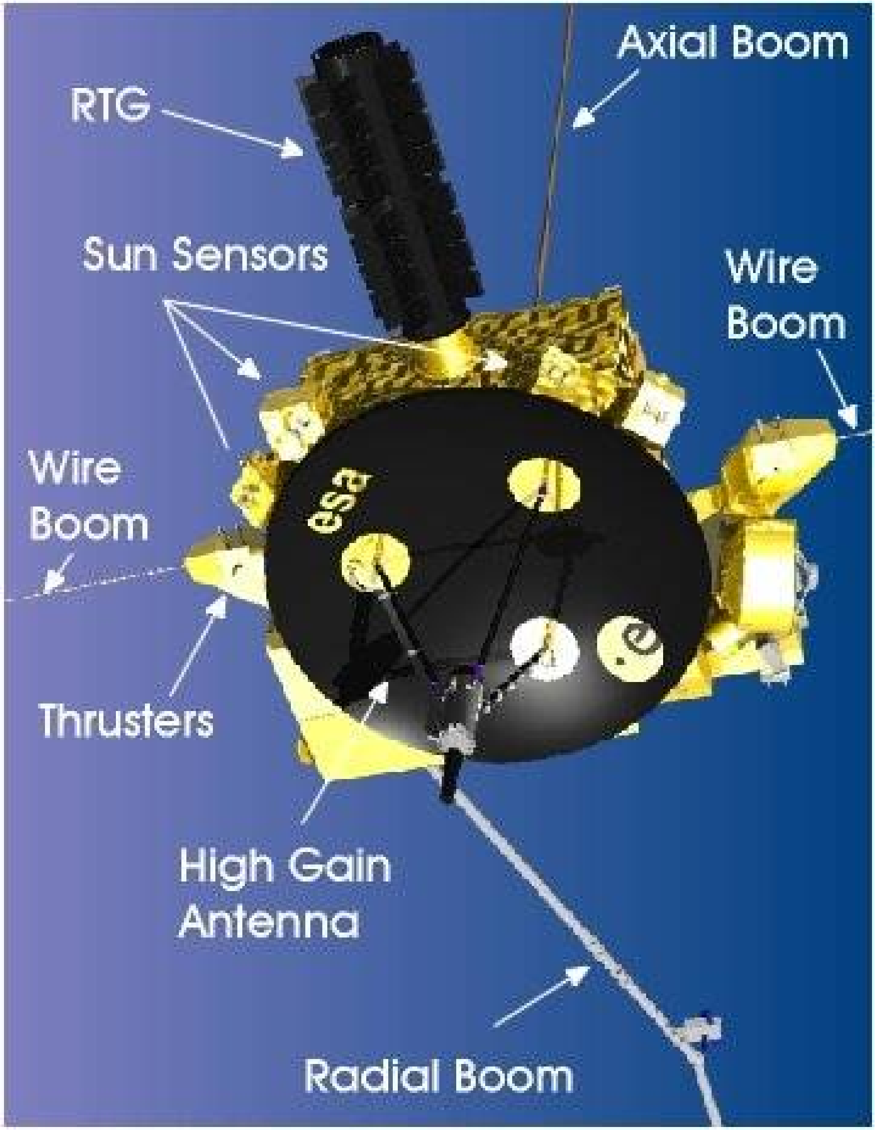
The Ulysses Spacecraft

Dimensions
- Length 3.2 m (booms stowed)
- Width 3.3 m
- Height 2.1 m

Mass
- Total at launch 366.7 kg
- Scientific payload 55.1 kg
- Payload cover ejected 0.1 kg

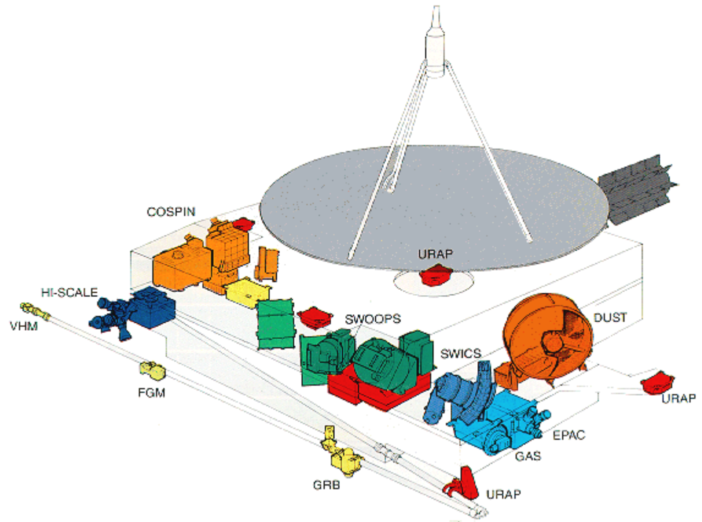
Power
- Radioisotope Thermoelectric Generator (RTG)
  - Beginning of mission 283 W
  - May 2006 ~200 W





The Ulysses Spacecraft- Payload

Ulysses' payload instruments come from a number of countries and institutes. Their aim is to explore the Sun, to understand how it works and assess its effect on the solar system by analysing the composition of the solar wind, studying cosmic rays, gamma-ray bursts, neutral gas and dust particles, and thereby provide the first-ever map of the heliosphere from the equator to the poles



Acronym	Instrument
COSPIN	Cosmic rays and solar particles
DUST	Cosmic dust
EPAC/GAS	Energetic particles and interstellar neutral gas
GRB	solar X-rays and cosmic gamma-ray bursts
HI-SCALE	Low-energy ions and electrons
SWICS	solar wind ion composition
SWOOPS	solar wind plasma
VHM/FGM	Magnetic field
URAP	Radio and plasma waves

The Ulysses Nutation Anomaly

Ulysses is a spin-stabilised spacecraft. A perfect spin motion can degenerate into nutation when a dynamic "imbalance" takes place.

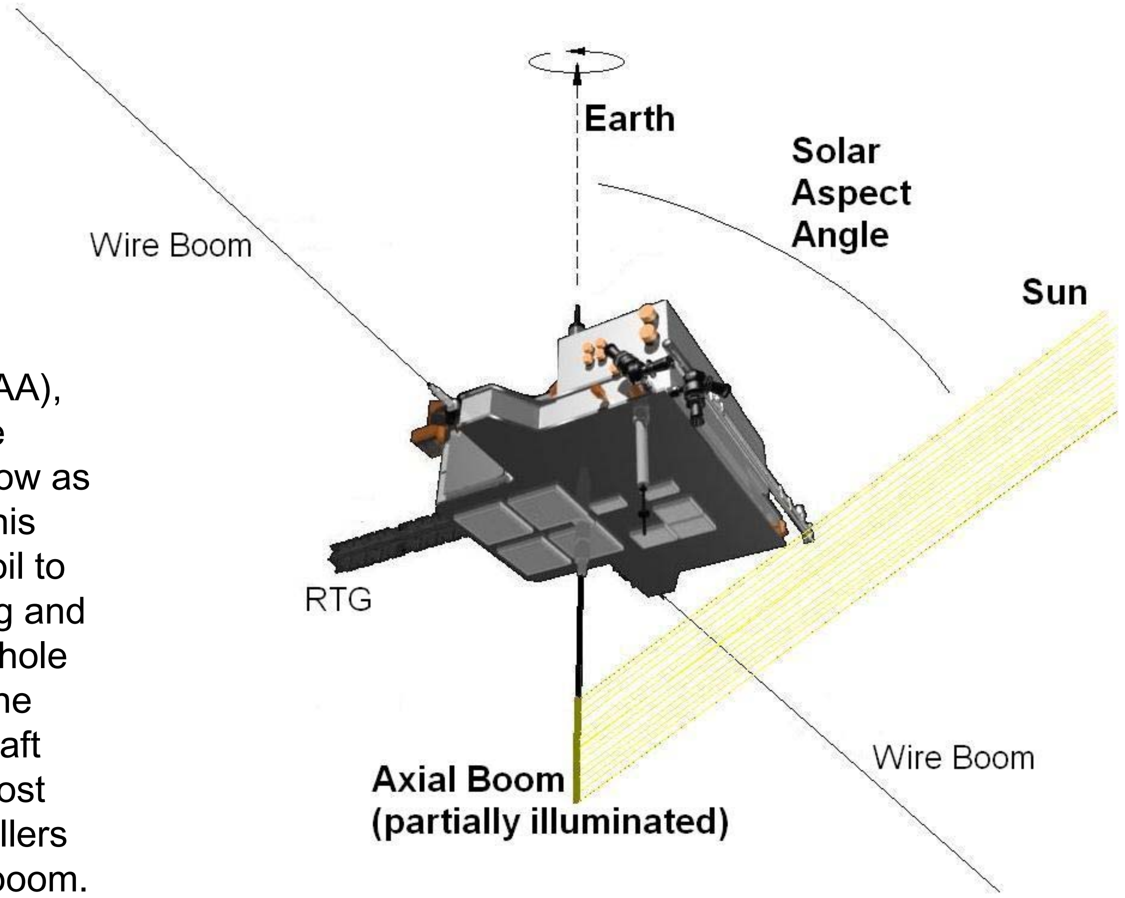
The nutation anomaly was discovered following deployment of the spacecraft's 7.5 M axial boom on November 4th, 1990. Investigations revealed the anomaly to be caused by solar pumping of the axial boom, combined with underperformance of passive nutation dampers on board the spacecraft.

Partially a function of heliocentric range, the anomaly returned for year-long periods in 1994-1995 and 2000-2001. During both seasons, the nutation was successfully controlled.

As Ulysses approaches and traverses perihelion, the anomaly will return for another season between February 14th 2007 and February 18th 2008.

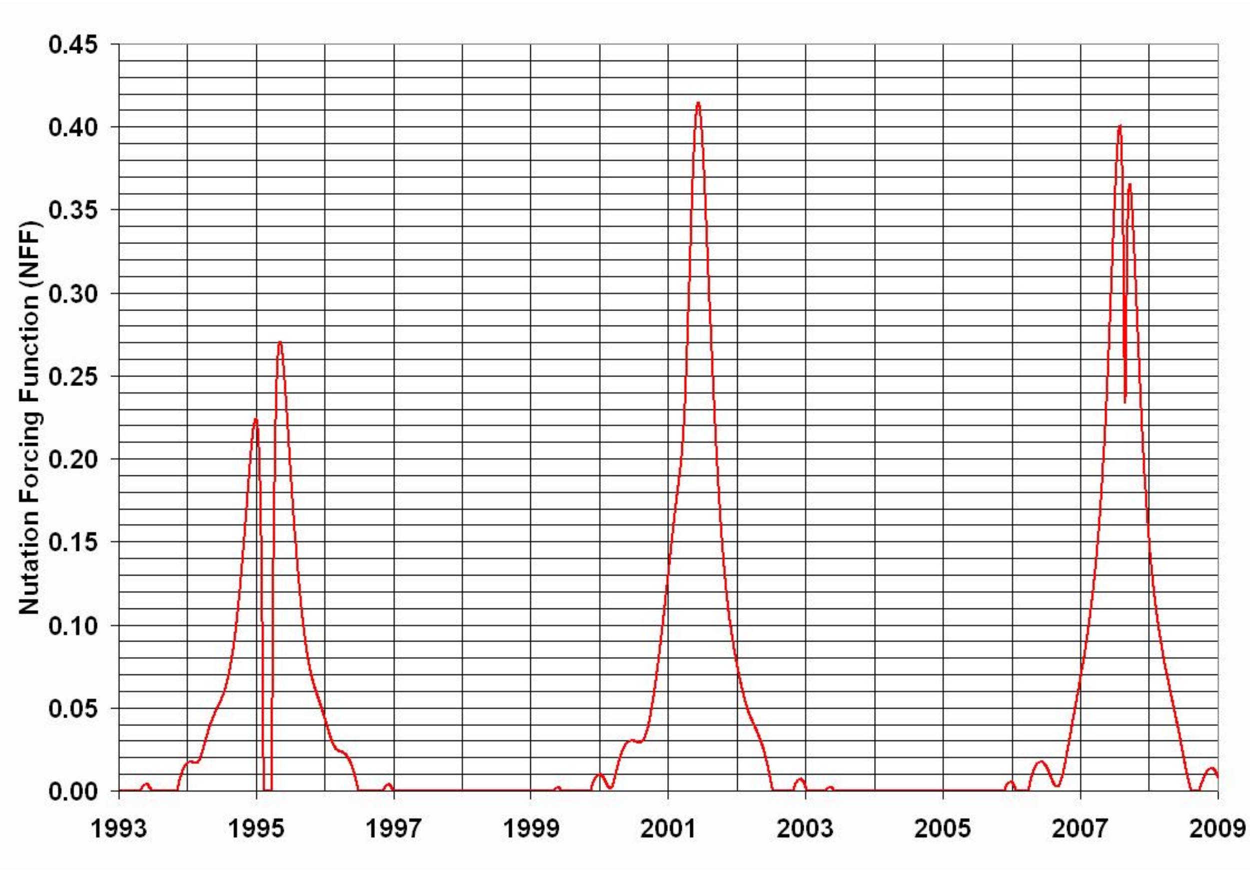
The following slides discuss the cause of the anomaly, and the induced effect on the spacecraft, after which means of nutation control will be discussed.

The Ulysses Nutation Anomaly



At certain solar ranges and certain spacecraft solar Aspect Angles (SAA), the two sides of the axial boom are alternately in partial Sun and shadow as the spacecraft rotates at 5 rpm. This causes the thin copper-beryllium foil to expand and contract due to heating and cooling effects. This causes the whole 7.5 m boom to flex.The flexing of the boom is transmitted to the spacecraft body because it was determined post launch that the axial boom drive rollers do not rigidly clamp the deployed boom. Thus the flexing boom “rattles” between the rollers.

The Ulysses Nutation Anomaly



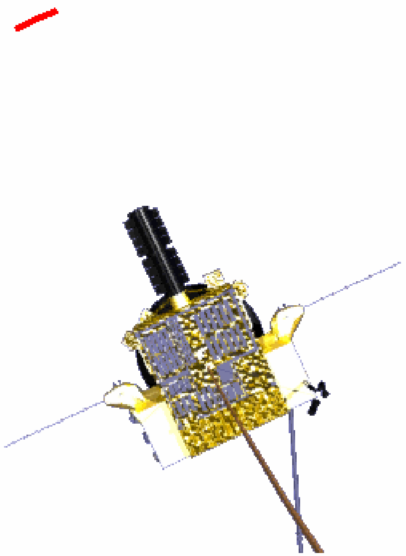
When the SAA is large enough to allow the boom to be illuminated, the Sun provides a continuous thermal input. When the SAA is of sufficient magnitude the driving force for nutation is ever present, meaning the level of nutation can increase. This is modelled by a “Nutation Forcing Function,” which is based on heliocentric range and Solar Aspect Angle (i.e. the portion of the boom exposed to sunlight).

For the upcoming nutation season, the NFF is, as shown in the diagram to the left, comparable in magnitude to the previous season, therefore similar build-up rates are to be expected.

The Ulysses Nutation Anomaly

The flexing of the axial boom results in dynamic instabiltiy of the spacecraft, which is described here.

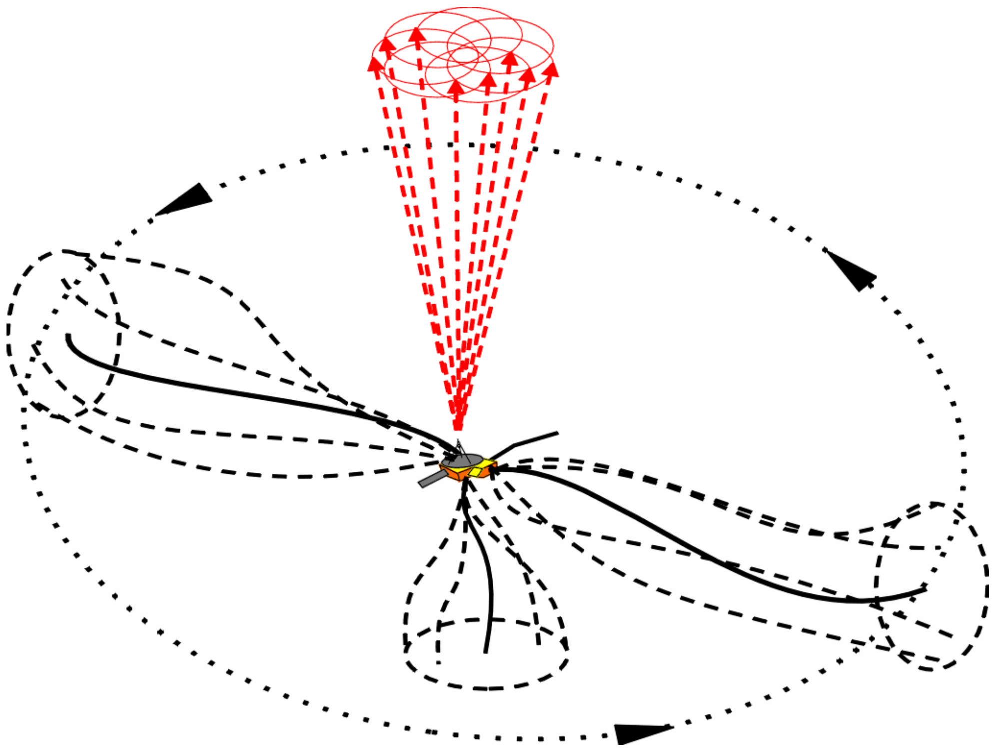
Imagine the spacecraft telemetry beam projected into the distance, tracing a red line in space. This line would trace out the pattern- a "nutation rosette“- in space. Characteristically, the spin axis goes through one full rosette in about 48 seconds, while the the spacecraft rotates about the spin axis once every twelve seconds (at a spin rate of 5 rpm), hence the nutation frequency is approximately one fourth the value of the spin frequency.



Outcomes of Uncontrolled Nutation

While this presentation will go on to discuss nutation control methods, and how they are applied, it is essential to understand some of the issues that could arise with insufficient nutation control.

This diagram illustrates possible flexure modes of the wire booms and antennae. If no attempt were made to damp the nutation, this could ultimately lead to loss of the spacecraft, or severe damage, should the wire booms wrap around the main body. They could potentially detach, leading to massive dynamic instability. The axial boom is also potentially subject to mechanical failure.



The nutation “rosette”, again depicted in red, shows the resulting pattern that the spacecraft telemetry beam would trace if projected into space as the spacecraft nutated. At the very least if nutation were left uncontrolled, it would cause a complete loss of spacecraft engineering and science data.

Outcomes of Uncontrolled Nutation

Beyond spacecraft health and safety, spacecraft nutation can impact mission science returns.

This can happen in two important ways. Firstly, high levels of nutation can affect the quality of telemetry received, as the spacecraft pointing accuracy varies.

Secondly, telemetry data that is received may be invalid due to the requirements of the instrument teams. The majority of the instrument teams can work to only a 0.5 degrees uncertainty in known attitude.

The year long period of nutation is also the period of prime scientific interest for this orbit. Therefore it is crucial that the loss of accurate data is minimised.

Nutation Control

There are a number of issues to consider in controlling nutation.

- How finely does nutation need to be controlled?
- What options are there for performing nutation control?
- What tools are available for monitoring nutation levels?
- What contingency options are available, for example due to ground station problems?

These issues are addressed on the following slides.

Nutation Control

The accepted Maximum Allowable nutation (MAN) level is 0.5 degrees half-cone angle. This limit is defined by:

- The ability to maintain a downlink
- The ability to maintain instrument pointing knowledge
- The ability to efficiently damp nutation

Means to control the nutation anomaly exist onboard the spacecraft. The Attitude and Orbit Control Electronics (AOCE) subsystem contains a closed-loop Conscan (CLC) function. When enabled the Conscan Electronics estimate how far the spacecraft spin axis is pointing away from Earth. It then calculates the phase angle at which to fire a thruster to try and reduce this off-pointing angle.

The Conscan Electronics can measure Earth off-pointing however , by nature, this equipment is very sensitive to changes in uplink signal strength, and interprets these as off-pointing. More on this later.

Coverage requirement is dependent on the severity of the nutation forcing function. In previous nutation seasons 24-hour coverage was available. This level of coverage is made infeasible due to the busy nature of the DSN, and the resulting level of priority assigned to the mission. Although it will prove operationally more challenging, the Ulysses project has reduced its requirement for the upcoming season to minimize its impact on DSN resources.

Nutation Control Tools- Closed Loop CONSCAN

- The Attitude and Orbit Control Electronics (AOCE) subsystem contains a **Closed-Loop Conscan** (CLC) function. When enabled, Conscan estimates how far the s/c spin axis is pointing away from Earth. It then calculates the phase angle at which to fire a thruster to try and reduce this off-pointing angle, commanding attitude control pulses to reduce the spacecraft's off-pointing from the Earth to within specific levels of deadband setting :
  - **wide (0.23°)**
  - **narrow (0.125°)**
- CLC measures for 2 spin cycles and fires on the third. Fortunately for Ulysses this means that when the thruster is fired, it not only provides a reduction in the off-pointing angle, but also a small component of damping. The thruster will keep firing every third spin cycle as long as CLC is enabled and the off-pointing is greater than the selected deadband.
- CLC can measure Earth off-pointing very well. However, by its very nature, it is very sensitive to changes in uplink signal strength, and interprets these as off-pointing. It therefore requires a stable uplink from a ground station.

Nutation Control Tools- Closed Loop CONSCAN

- Successful CLC depends on steady uplink power.

  Conscan measurement strongly affected by

  - **Power level**: U/L must be smooth and stable for as long as possible. Watch for power drift.
  - **Command modulation**: Only switch ON or OFF when scheduled or requested by ACE
  - **Polarization**: U/L must be RCP. Wrong polarization is very, very bad!!!
  - **Antenna tracking:** Problems with subreflector or tracking quickly gives erroneous Conscan measurements.

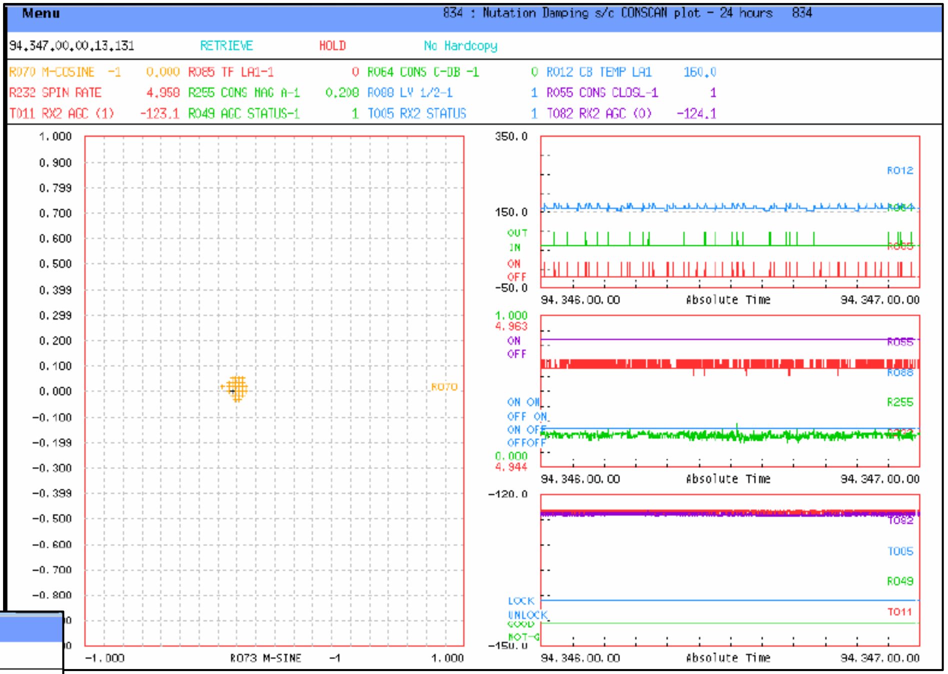
- Must not use ground Conscan

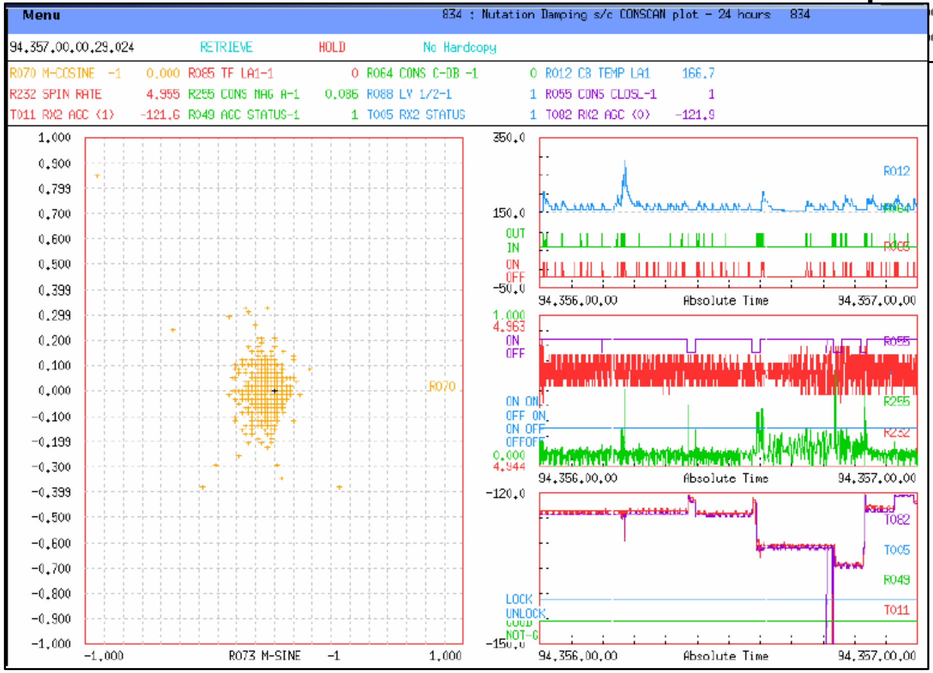
  An important constraint for all Ulysses uplink antennas is that Ground CONSCAN is not allowed unless the on-board closed loop conscan control is disabled. Otherwise the result would be “duelling Conscans,” as the onboard CLC relies on a stable uplink signal as a beacon.

- In previous nutation seasons continuous coverage was available, wjhich is no longer the case. Extensive analyses have been performed to estimate the maximum gaps in CONSCAN that can be tolerated throughout the upcoming nutation season and will be discussed later on.

Nutation Control Tools -SMCS

SCMS- The Spacecraft Control and Monitoring System allows the Flight Control Team to monitor spacecraft parameters such as thruster firings, spin rate, receiver AGC level.



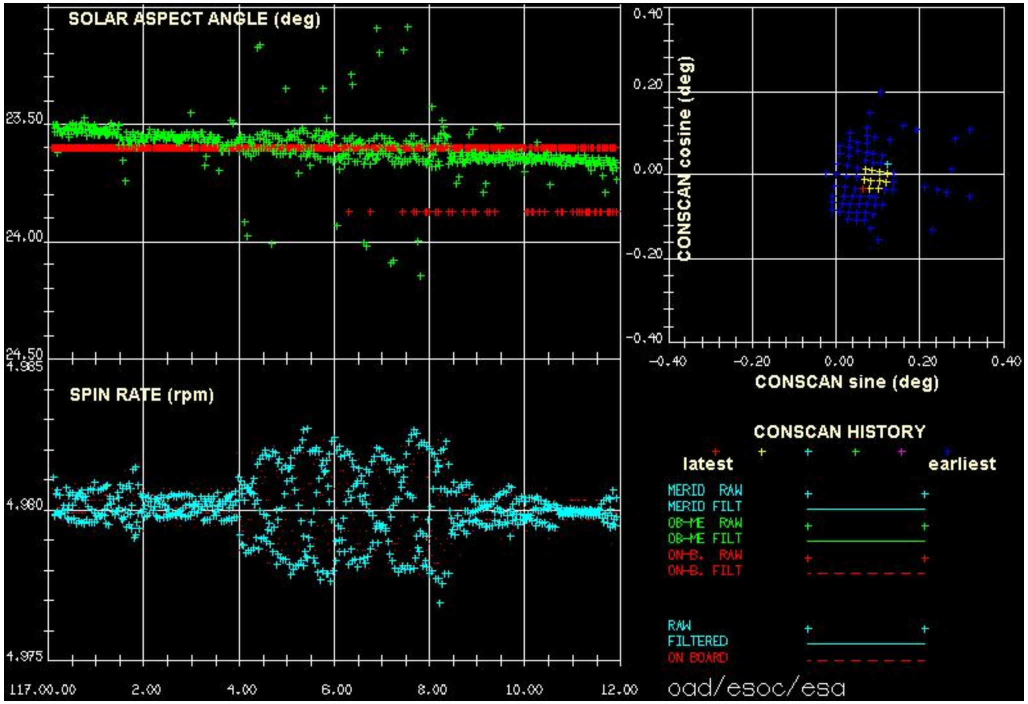


Seen here are two instances of an SCMS display used to monitor nutation operations. The window above is from a period of fairly low nutation, the window to the left showing a period during which nutation was seen to be higher.

Notice the main plot in each window. The central point represents the spin axis, while the surrounding “cloud” of points representing CONSCAN measurements is much tighter around this central point on the period of lower nutation.

Nutation Control Tools- RPMS

The **Routine Phase Management System** (RPMS) is effectively an umbrella for a number of elements of Ulysses Flight Dynamics software. One of the functions of RPMS is to monitor spacecraft attitude and related subsystem parameters. Seen here is an example of an RPMS output covering a number of attitude parameters.



Nutation Control Tools- ARGOS

TO BE UPDATED FOR NEW DEVELOPMENT OF ARGOS

In the previous nutation seasons it proved difficult to obtain reliable attitude estimates from spacecraft telemetry. Alternate sources of attitude and manoeuvre information were sought.

One of these was a piece of software known as **ARGOS** (Attitude Reckoning from Ground Observable Signals). ARGOS processes the modulation of the spacecraft radio-signal, providing real-time estimates of different parameters, including:

- **Half Cone Nutation Angle (NuTH)**

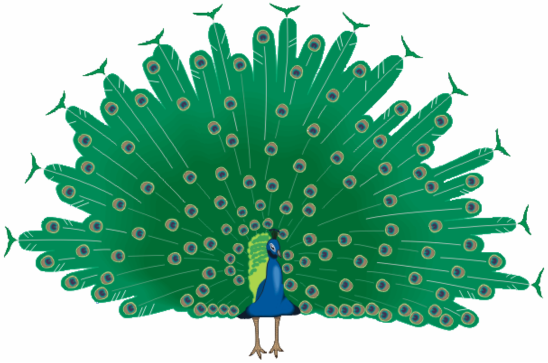
  Half the magnitude of the nutation angle.

- **Earth Aspect Angle (EAA)**
- **Spacecraft Spin (SPIN)**

  The spin rate of the spacecraft.

- **Meridian Antisymmetric (MA)**

  This refers to the half-cone amplitude of the oscillation mode produced by the 72.5m flexible wire booms.



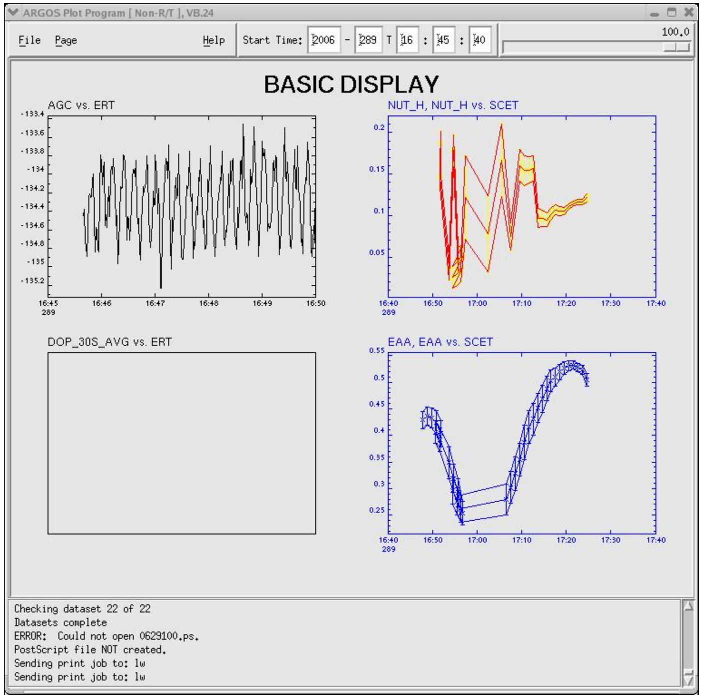
In Greek mythology Argos is a hundred-eyed, ever-vigilant giant, a servant of Hera. Upon his death, Hera decorated the peacock's tail with 100 eyes in Argos' memory. Conveniently Argos is also the name of Ulysses' faithful dog, as described in "The Odyssey".
Attitude data (RPMS)

Nutation Control Tools- ARGOS

TO BE UPDATED FOR NEW DEVELOPMENT OF ARGOS

The directional gain pattern of the antenna aboard the spacecraft makes radio signal strength measurements an effective means of determining spacecraft attitude. Taken into account along with the Doppler observations provided simultaneously by the DSN tracking stations, these measurements may be used to produce real time estimates of the timing and delta-v magnitude of the manoeuvre pulses.

ARGOS uses no onboard hardware or software. The only requirement on the spacecraft is transmission of its carrier radio signal, while the ground station is required to be able to deliver high-rate Doppler data (10 samples per second). ARGOS is designed to detect attitude dynamics in the 0.02 to 1.0 degree range with a 0.0005 degree accuracy, and a one-minute update rate. Attitude control delta-vs are measured with an accuracy of up to 0.1 mm/s. In previous seasons with continuous coverage this provided near real time information for decision making if and when nutation built up. Without continuous coverage in the upcoming season, it is likely to be a case of when, rather than if there is a nutation build up.



Nutation Control Tools- PHAEACIAN

For a more detailed PHAEACIAN presentation, click here

During a period of nutation, the Flight Control Team (FCT) may have a number of options open to them as they try to minimise the nutation angle, this includes altering the deadbands of the onboard conical scanning system (CONSCAN), or performing specific manoeuvres designed to provide a large one-off offpointing that the CONSCAN system may be able to damp more easily than ongoing nutation.

At any time, one option may or may not work as expected, due to the inherent unpredictability of nutation. Further, multiple options may offer similar results and levels of success. The selection of these options comes down to the experience and knowledge of the FCT.

Prior to the 2000-2001 nutation season, a tool was envisioned that would aid in the decision making process. Trying to translate human language rules such as “If the nutation angle is quite large then…” the potential for using fuzzy logic rules became apparent.

This tool became known as **PHAEACIAN** (Program Handling Argos Estimates And Calculating Intelligent Actions for nutation), the basic goals of which are:

- Recommend actions based on past and current experience of the Flight Control Team in similar situations, using Fuzzy Logic techniques
- Assist the Flight Control Team during nutation anomaly monitoring and trend reporting (by automating the extraction from ARGOS output files and graphical plots of the parameters involved in the nutation operations)
- Assist the Associate Cognizant Engineer (ACE, NASA spacecraft controller) in preventing real-time contingencies, thus reducing the need for continuous spacecraft operation’s engineer support.

Nutation Control Tools- PHAEACIAN

For a more detailed PHAEACIAN presentation, click here

Created with MATLAB, using the Simulink and Fuzzy Logic Toolbox modules, PHAEACIAN consists of a model and GUI, taking its input from the earlier-mentioned program, ARGOS (Attitude Reckoning from Ground Observable Signals).

PHAEACIAN can be used in two modes:

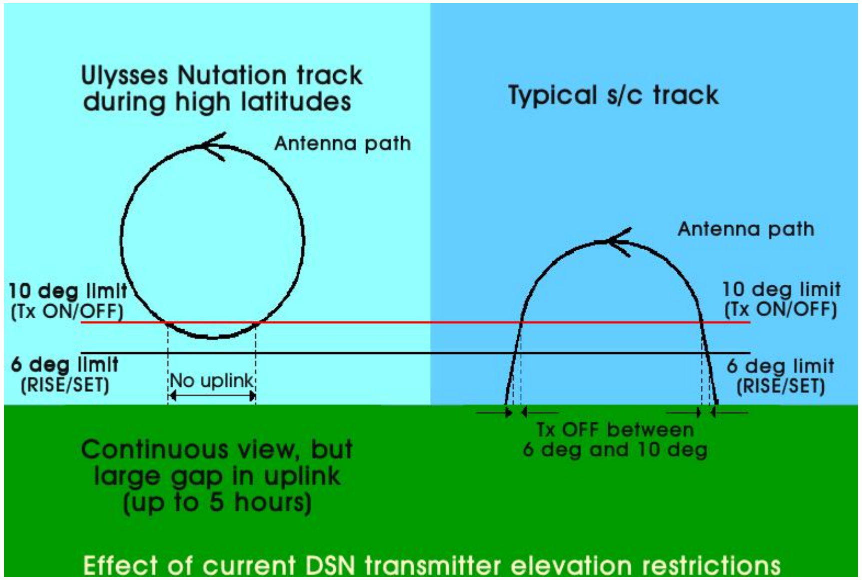
- The off-line mode allows the user to read and replay historical ARGOS files. It has been used to develop and test the application. It can be used to support the PHAEACIAN rule-base fine-tuning.
- The on-line mode reads incoming ARGOS files and imports the necessary data into the application. PHAEACIAN recognizes invalid data and interpolates the data to provide the necessary inputs for fuzzy logic (FL) system.

Ground Station Coverage

The DSN is designed primarily for in-ecliptic spacecraft. Ulysses' unique orbit has some interesting consequences:

- No visibility or continuous visibility from a single DSN complex during high latitude phases
- Gaps in coverage
- Cable-wrap and keyhole events

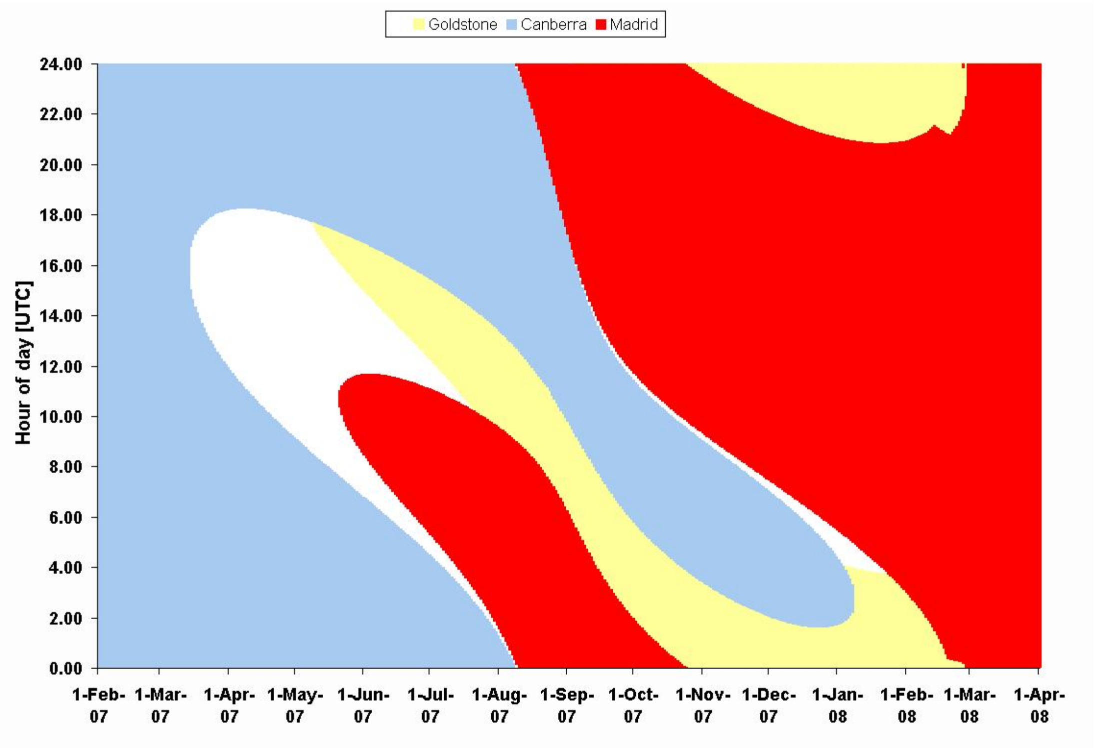
While in some cases the orbit can afford longer viewperiods- even continuous, the actual allocation of resource time is affected by user loading on the network.



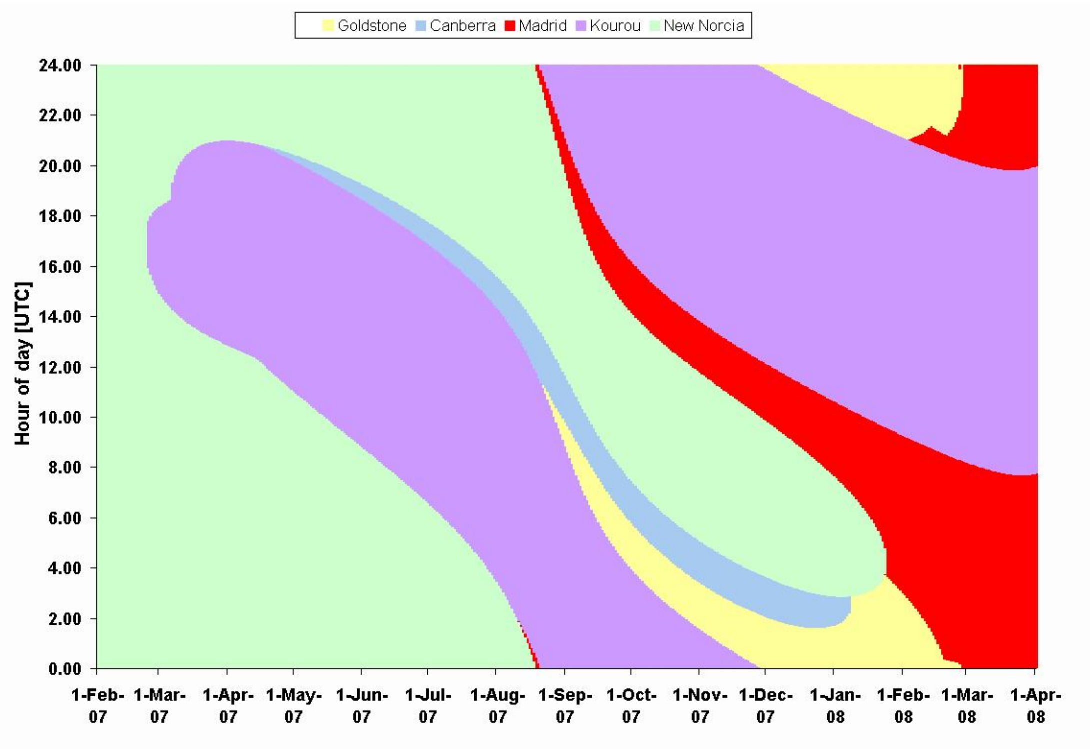
DSN Visibility (Uplink)

As mentioned previously, twenty-four hour coverage is not possible in the upcoming nutation season. While heavy user requirements are a key reason behind this, there are also times where there is simply no view from any DSN station. The chart below shows the Ulysses view periods- above 10-degree elevation- of the DSN complexes for the period of the nutation season, but takes no account of station availability and user loading. Note the two gaps (areas in white), where there is no view at certain points in the day.

While operations will be planned to work around non- continuous coverage, it is important to be able to close or minimise these gaps in view wherever possible. A twenty-four hour a day view period does not mean Ulysses can receive twenty-four hour tracking- as well as maintenance constraints, there are of course the other missions requiring portions of that time. Being able to fill in these gaps in view increases the opportunity to schedule ground station coverage.



DSN + New Norcia + Kourou Visibility

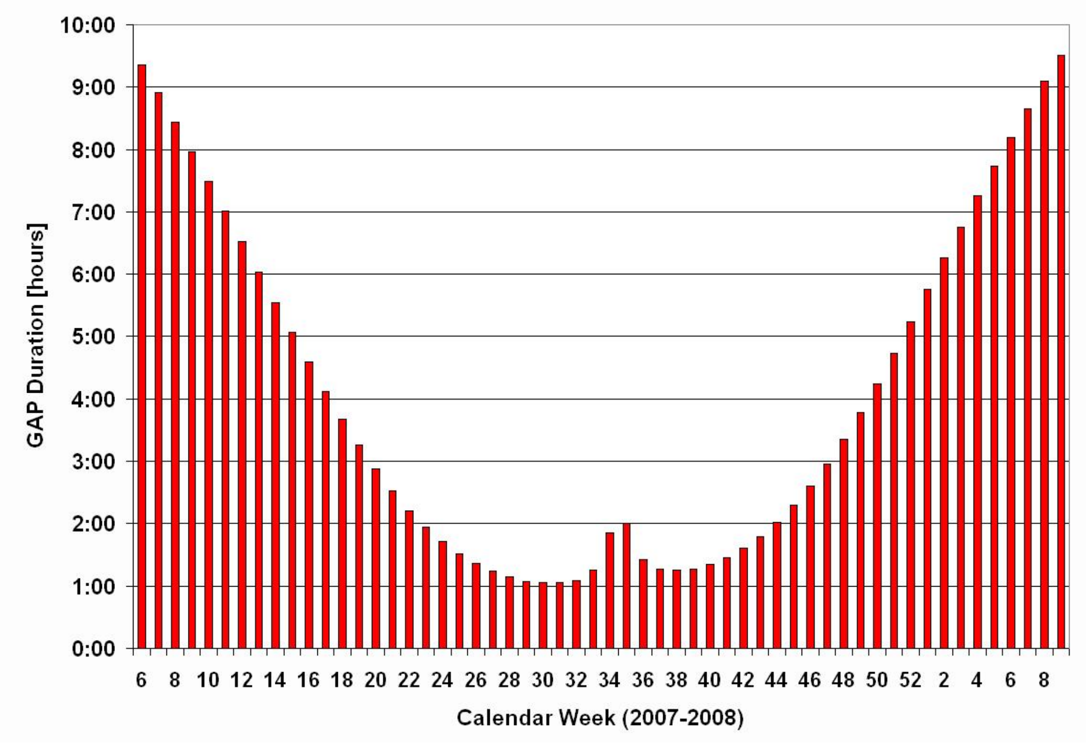


In this chart, the view periods of two ESA ground stations are superimposed on the previous plot. New Norcia, in Australia, is offset from Canberra enough to lessen the first large gap, and effectively close the second gap in potential coverage. Kourou, in French Guiana, provides view periods that would fill the first gap. As with the previous graph, this is simply showing view periods, and not taking account of availability or user loading on the ESA stations.

Maximum Allowable Gaps in CONSCAN

Having looked at some of the physical possibilities of view periods, and discussion of the related constraints- for example other missions or maintenance schedules- it is useful to look from a different point of view, and discuss the minimum amount of time required to control nutation.

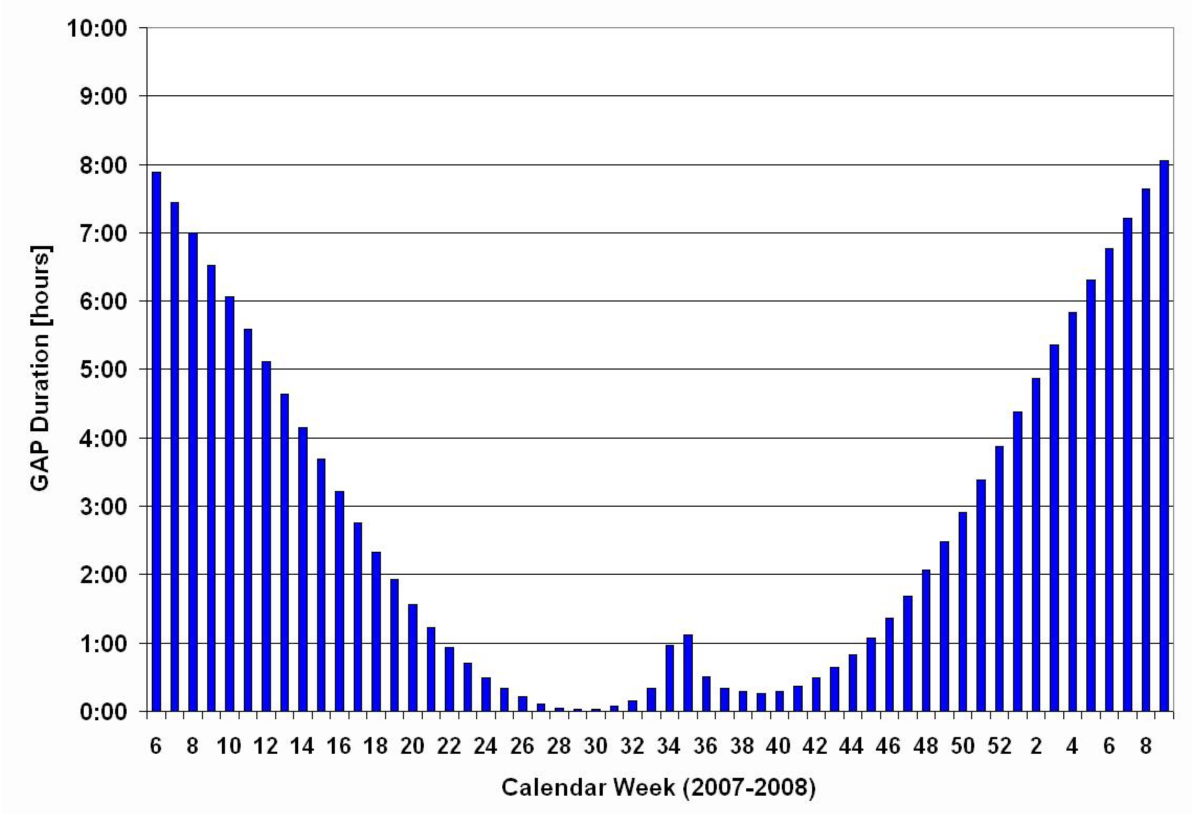
On a week by week basis, this chart shows the "MAGICONSCAN" number- the length of time Ulysses can go without having Closed Loop Conscan enabled, before the predicted nutation levels build up to an unacceptable level.



Note the shape of the plot is effectively an inversion of the predicted forcing function, the greater the forcing function, the less time the spacecraft can safely operate without a period of CONSCAN operation.

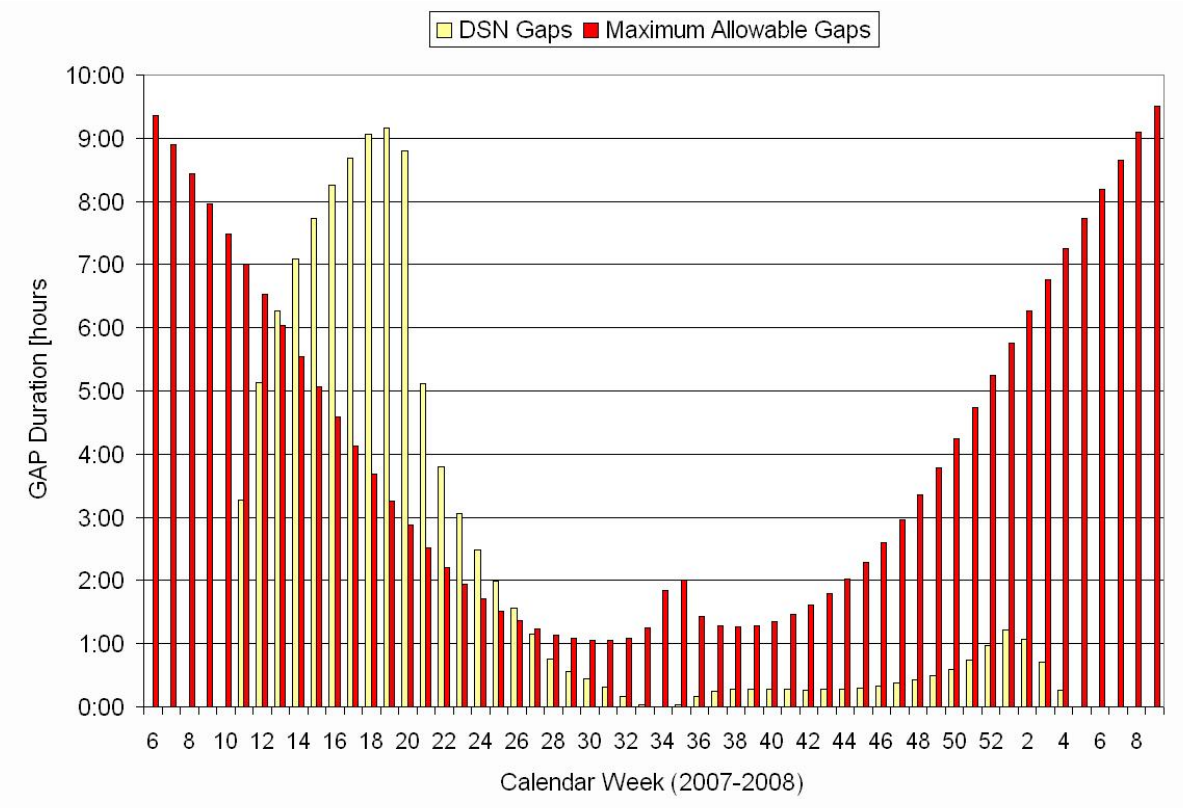
Maximum Allowable Gaps in Coverage

A related number is the “MAGIC” number- the greatest length of time Ulysses can go without ground station coverage, shown here on a week by week basis.



DSN Gaps in Uplink and Maximum Allowable Gaps in CONSCAN

Combined here are the curves for the MAGICONSCAN Number and the gaps in DSN coverage. In the early part of the season and the second half of the season, the MAGICONSCAN value is greater than the gaps in DSN visibility. In weeks 13 to 26 of 2007, this is not the case, and is where ESTRACK coverage is required to fill the gaps.



Comparison to Previous Nutation Seasons

For the upcoming season, unlike in previous cases, there will be limited ground coverage available for Ulysses, which is needed for nutation control.

Max Earth drift rate: 3°/day (0.85°/day in 1995 and 1.30°/day in 2001)

Lower power available due to RTG decay

- Limits the operational flexibility (mutually-exclusive activities) and erodes thermal margins

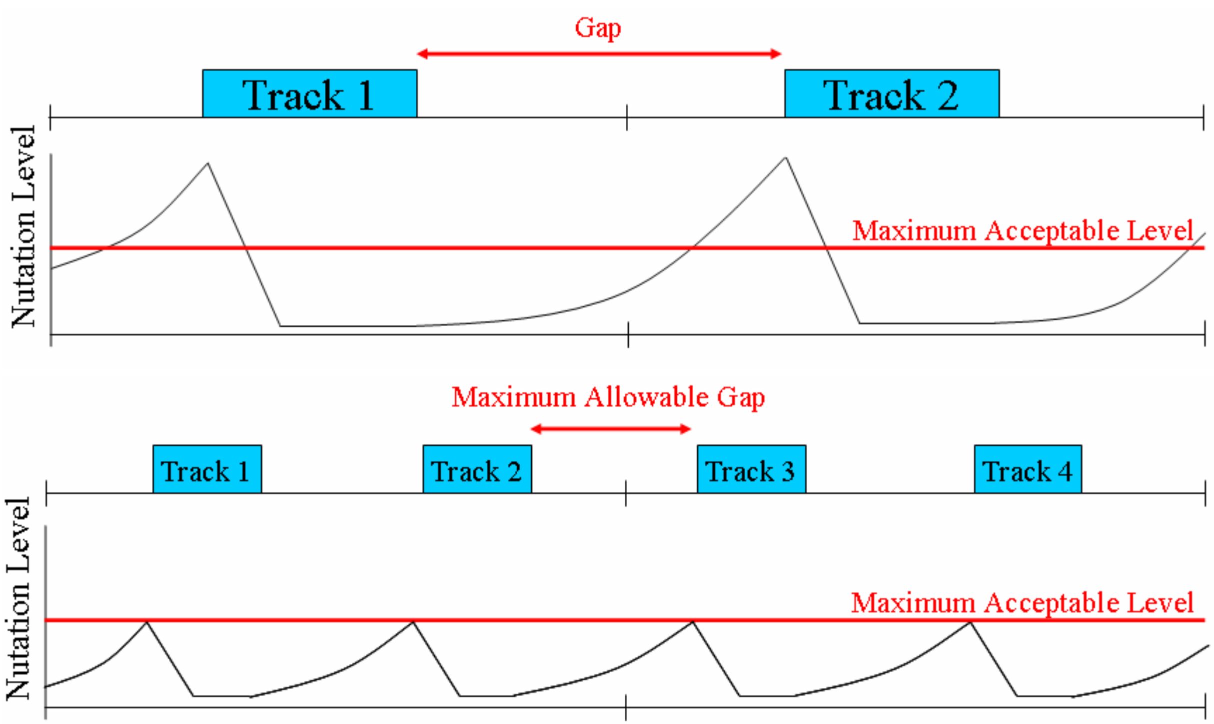
The ARGOS data from the previous nutation season was analyzed in detail to produce estimates of the nutation build-up rates (as a function of NFF) and the nutation damping performance of closed-loop CONSCAN.

The upcoming nutation season was analyzed in terms of various parameters such as the nutation forcing function, Earth drift rate, link budgets and margins at various bit rates and spacecraft off pointing values, ground station coverage, etc. Estimates of the “Maximum Allowable Gap in CONSCAN operations” (MAGICONSCAN) and the “Maximum Allowable Gap in Coverage” were made.

The upcoming season introduces some new operational challenges: the reduced coverage shall limit CONSCAN operations and higher levels of nutation are to be expected. The Earth drift rate shall reach values never seen before (up to 3 degrees/day). Power and thermal issues pose major constraints on the operations as well (e.g. no playback during CONSCAN while the cold-case heater is on).

Nutation Operations 2007-2008

The intention is to move from a philosophy of from one large pass to numerous smaller passes throughout the day. Each pass will begin with a period of enabled Closed Loop Conscan.



CLC will be enabled as the uplink hits the spacecraft, sometime after the start of track.

Data recorded on the DSUs (Data Storage Units) will then be played back at as high a data rate as possible.

CLC will be activated whenever DSU playback is not taking place during a pass, to further mitigate nutation build up.

Conclusions

Nutation has to be controlled in order to:

- Maintain spacecraft health and safety
- Maximise scientific data return during mission's prime science phase

DSN cannot meet coverage requirements between weeks 13-26 in 2007

- Negotiations to fill the gap in coverage with ESTRACK stations (New Norcia and Kourou) are taking place

This is the first nutation season where continuous coverage will not be available.

Further Links

Ulysses section of ESA Science:

- http://sci.esa.int/ulysses/

ESA Ulysses science:

- http://helio.estec.esa.int/ulysses/
- http://ulysses-ops.jpl.esa.int/ulysses/ (mirror site)

JPL Ulysses science:

- http://ulysses.jpl.nasa.gov/

Ulysses mission operations:

- http://ulysses-ops.jpl.esa.int/